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# Analog Filter Design Rules for Multilevel Polybinary Signaling Generation

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**Abstract:** Polybinary signaling has gained attention lately due to its generation simplicity and reduced spectral usage. This paper presents a study on the requirements for analog filters for the generation of multilevel polybinary signals with three to nine levels.

**OCIS codes:** (060.0060) Fiber optics and optical communications; (060.2360) Fiber optics links and subsystems.

## 1. Introduction

Bandwidth demands are driving the development required to realize high capacity data transmission systems based on optical technologies for short and client side scenarios. At the physical layer, the most visible result of these efforts is seen in the quest for higher bitrates in a single channel or per single lane. Increasing the capacity of a single channel is usually obtained by increasing the spectral efficiency with the help of advanced modulation formats. Polybinary signaling [1] was first proposed to precisely increase the spectral efficiency by exploiting intersymbol interference (ISI). The most popular polybinary signaling scheme is duobinary, which consists of a three level modulation format [2]. Duobinary signaling has been extensively used in datacom backplanes, due to the low-band pass filter performance of the backplane channel that nearly fits the duobinary filtering, and it is now entering the optical access arena through systems like XLG-PON, providing 40Gbit/s downstreams in a PON system using duobinary signaling.

Duobinary modulation is in fact a particular case of the family of polybinary signaling. Polybinary signals can actually have as many as  $M$  levels, as early identified in [1]. Current reported demonstrations of polybinary signaling include five level at 10 Gbit/s [3-4], seven levels at 14 Gbit/s [5] and even seven levels at 112 Gbit/s [6]. The principle of polybinary generation is based on adding a controlled amount of inter-symbol interference (ISI) by mean of coding, and then removing the undesired frequency components of the signal using a low-passband filter. Hence, there is a need to identify the features of the low-passband filter design that secure efficient generation of  $M$  level polybinary signals. This paper addresses this need by providing a roadmap of frequency cut-off requirements for polybinary signals with three to nine levels.

## 2. Theoretical background

Polybinary signaling is a partial-response transmission format, which makes use of bit correlation to reduce the spectral width. This correlation is introduced through an amount of controlled ISI. This controlled ISI is introduced by a simple codification scheme [1-6]:

$$\begin{aligned} b_k &= a_k \oplus b_{k-1} \oplus \dots \oplus b_{k-n} \\ c_k &= b_k + b_{k-1} + \dots + b_{k-n} \\ a_k &= c_k \bmod 2 \end{aligned} \tag{1}$$

Where  $a_k$  is original bit sequence,  $n$  the number of levels,  $b_k$  a precoded polybinary sequence, and  $c_k$  the polybinary generated signal. By respecting this set of relations, it is possible to recover the original binary sequence from independent decisions on  $c_k$ . Once the coding is conducted, a low pass filter (LPF) is generally used to remove the undesired frequency components. There have been many research efforts to optimize the LPF's bandwidth in duobinary systems: at 10 Gbps receiver sensitivity has shown to be improved by employing a 3 GHz LPF and better amplified spontaneous emission (ASE) noise limited performance can be achieved with 2.8 GHz. In polybinary signaling, Bessel filters are used because of their maximally flat group/phase delay (maximally linear phase response), which preserves the wave shape of filtered signals in the passband.

Figure 1 shows the performance of a duobinary signal in terms of bit error rate (BER) performance, signal to noise ratio (SNR) and frequency cutoff of the filter used to generate the polybinary signal. Furthermore, Fig. 1 also shows the evolution of a non-return to zero (NRZ) signal when filtered at different normalized frequencies.

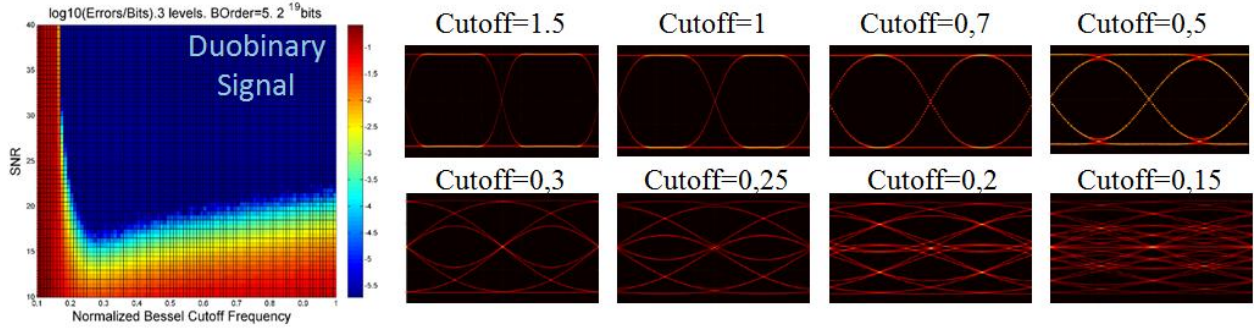


Fig. 1. BER performance for different SNR levels and frequency cutoff frequencies of a duobinary signal. Evolution of a regular non-return to zero signal when filtered at different frequency cutoff points; narrower filtering generates higher order polybinary signals.

### 3. Numerical simulation results

In order to generate a roadmap of analog filter requirements for the generation of polybinary signaling, we conducted numerical simulations emulating a transmitter and a receiver end-to-end performance. Two design parameters of the filter, i.e. the frequency cutoff and the filter order, and one signal feature, the SNR, were swiped against BER performance for five, seven and nine levels polybinary. Figure 2 shows the 2-dimension (2D) performance map for five, seven and nine levels polybinary, respectively.

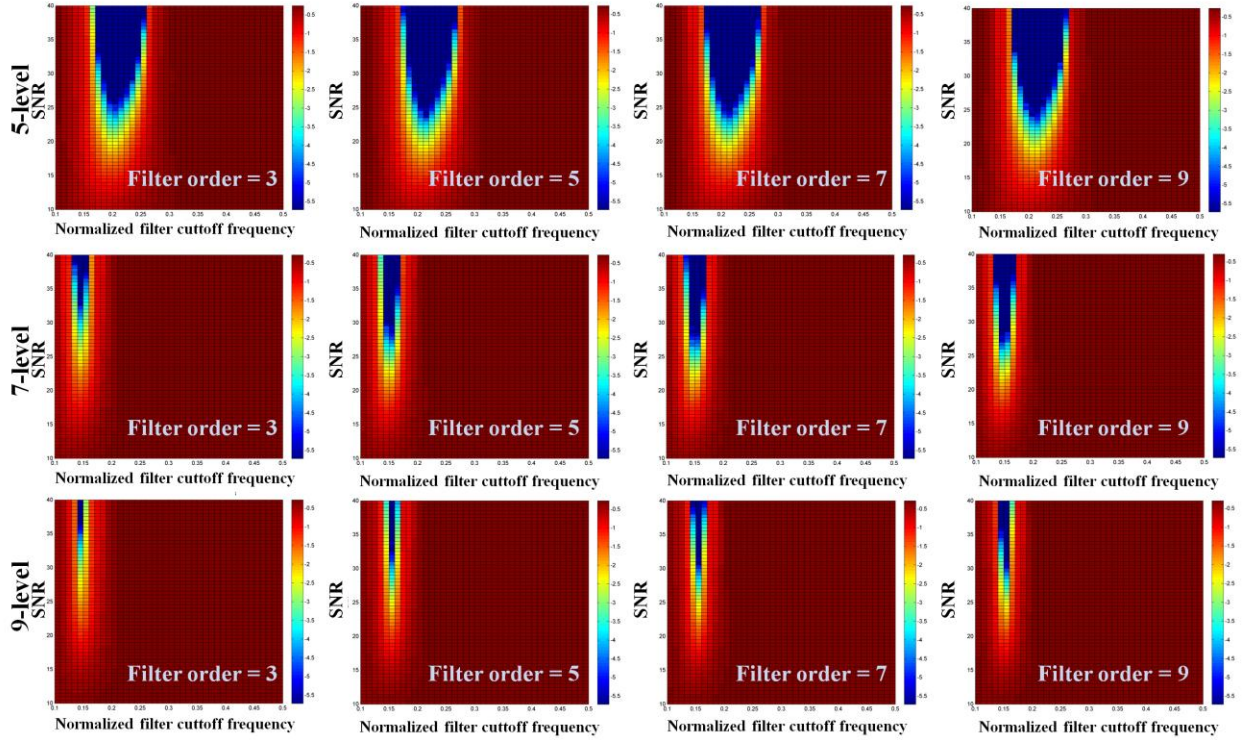


Fig. 2D maps of BER performance for five, seven and nine level polybinary generation.

As it can be observed from the 2D maps of BER results, by increasing the filter order, better BER values can be achieved with lower SNR requirements. The frequency ranges of generation for each polybinary level remains independent of the filter order.

Table 1 provides an overview of the main polybinary generation features, including the number of amplitude thresholds at the receiver side, an approximate spectral efficiency and the minimum SNR requirement for error free BER performance considering forward-error correction (FEC), along with the main features of 4- and 8-PAM, for comparison purposes. As it can be observed, regardless the levels in the polybinary modulation, the complexity in

terms of amplitude thresholds to be placed at the receiver are in the same order of magnitude than for PAM modulation. However, the spectral efficiency is slightly higher. The ranges of generation for five levels are between 17-26% of the normalized frequency cut off, whereas seven levels require between 13-17%. Nine levels require a challenging frequency cut off between 12-13% of the normalized frequency, which requires a tight control on the profile of the filter.

Table 1. Summary of polybinary generation features. \*10 Gbaud with pulse Gaussian shapping of 7.5 GHz at 3 dB bandwidth.

PRM		5 Levels	7 Levels	9 Levels	4-PAM	8-PAM
Amplitude Thresholds		4	6	8	3	7
Spectral Efficiency		~5 Bit/s/Hz	~7 Bit/s/Hz	~7.5 Bit/s/Hz	~2 Bit/s/Hz	~4 Bit/s/Hz
Minimum SNR for Maximum measurable BER	<b>BOrder 3</b>	~24.5 dB	~29.5dB	~30 dB	~18 dB*	~22 dB*
	<b>BOrder 5</b>	~23.5 dB	~26 dB	~ 28 dB		
	<b>BOrder 7</b>		~25 dB			
	<b>BOrder 9</b>					

#### 4. Conclusions

Polybinary signaling provides an efficient and simple solution to transmit data in bandwidth limited channels, or alternatively, to increase the capacity of existing channels by making a more efficient use of the available bandwidth. As the generation process is based on electrical filtering, a roadmap of requirements on the filter design for proper generation is necessary. This paper provides a study on the filter requirements for five, seven and nine levels polybinary at 10Gbit/s. Five and seven levels have filter requirements relatively relaxed in terms of filter accuracy, ranging from 12 to 26% of the normalized frequency. Nine levels polybinary signaling requires a high degree of finesse on the frequency cutoff allowing little deviation, in the order of 12% of the normalized frequency. A significant finding is the decorrelation between the filter order and the generation of polybinary signaling, allowing for relaxed requirements on the electrical analog filter.

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